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EFFECT OF TEMPERATURE UPON THE DISCHARGE OF ELECTRICITY FROM METALS ILLUMINATED BY ULTRA-VIOLET LIGHT

A DISSERTATION

SUBMITTED TO THE FACULTY OF THE OGDEN GRADUATE SCHOOL OF SCIENCE IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

(DEPARTMENT OF PHYSICS)

BY

GEORGE WINCHESTER

CHICAGO
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THE EFFECT OF TEMPERATURE UPON THE DISCHARGE OF ELECTRICITY FROM METALS ILLUMINATED BY ULTRA-VIOLET LIGHT.

BY GEORGE WINCHESTER.

I. INTRODUCTION.

THE influence of temperature upon the discharge of electricity from metals illuminated by ultra-violet light has been studied by Hoor,[1] Stroletow,[2] Elster and Geitel,[3] Righi,[4] Zeleny[5] and J. J. Thomson.[6] The early investigations did not produce results capable of definite interpretation because in those experiments a gas surrounded the metal and its influence and effects were unknown. Hoor and Stroletow obtained conflicting results — Hoor found that the current from a zinc surface decreased as the temperature rose and Stroletow found the current rising with the temperature. Elster and Geitel found that the current from zinc was independent of the temperature. Righi found that the positive charge taken up by a hot plate was greater than that taken up by a cold plate; air currents set up by the hot metal may have influenced this result. Zeleny's results from experiments upon iron and platinum at atmospheric pressure bring out several interesting phenomena yet they shed no light upon the question of whether or not there is any change in the photo-electric effect due to a change in the temperature of the molecule, because of the unknown influence which the surrounding gas might have on the results. Elster and Geitel found that the current from a potassium surface in a good vacuum when its temperature changed from 20.3 to 50.3 was increased

[1] Hoor, Wien. Berichte, Vol. 97, p. 719, 1888.
[2] Stroletow, Comptes Rendus, Vol. 108, p. 1241, 1889.
[3] J. Elster and H. Geitel, Wied. Ann., Vol. 48, p. 625, 1893.
[4] Righi, Atti. Ist. Ven., 7-Mem. 11.
[5] Zeleny, PHYS. REV., Vol. 12, p. 321, 1901.
[6] J. J. Thomson, Conduction of Electricity through Gases, p. 239.

nearly 60 per cent. J. J. Thomson in his book on Conductivity of Electricity through Gases refers to some work by himself in which the alkali metals were heated to a temperature of about 200° C. in a good vacuum ; he also found a very great increase in the current. E. Ladenburg[1] investigated the relative rates of discharge from the ordinary metals in a high vacuum but did not alter the temperature. He found that the rate of discharge depended much upon the condition of the electrode ; *i. e.*, upon the method and degree of polish of the surface ; also, that the value changed with the time. Just what change is produced in the electrode so as to alter the photo-electric effect he does not make clear.

The principal object in the present investigation has been to find out whether or not there is any temperature effect when the disturbing influence of the surrounding gas has been removed ; *i. e.*, with an increase of energy of translation of the molecule is there also an increase of subatomic energy shown by an increased photo-electric effect ? In the preparation of the metal disks as well as throughout the experiment, care was taken that all the different metals received the same treatment, and that the ultra-violet light acted upon the different metals under exactly similar conditions.

II. Description of Apparatus.

The apparatus which is shown in Fig. 1 consisted of a large glass bulb (Fig. 2) within which was mounted a circular aluminium disk used as a support for the different metals employed. The wheel was under magnetic control so that any metal might be rotated to a position in front of the source producing the ultra-violet light. The wheel was mounted on agate bearings and was balanced so that it would remain at rest when rotated into any position. Across the back of the wheel was fastened a small bar magnet to facilitate its rotation, which was accomplished by means of a large horse-shoe magnet ; in order that the wheel might be connected to the electrode outside the bulb, a platinum spring was used to place it in contact with the frame as is shown in the figure. The frame was in direct connection with the electrode. Metal disks of copper, nickel, iron, zinc, silver, magnesium, lead, antimony, gold, aluminium and brass,

[1] E. Ladenburg, Ann. d. Phys., Vol. 12, p. 558, 1903.

each disk one centimeter in diameter, were attached to the circumference of the wheel. The disks were screwed to the aluminium wheel and polished with dry emery so as to be free from the presence

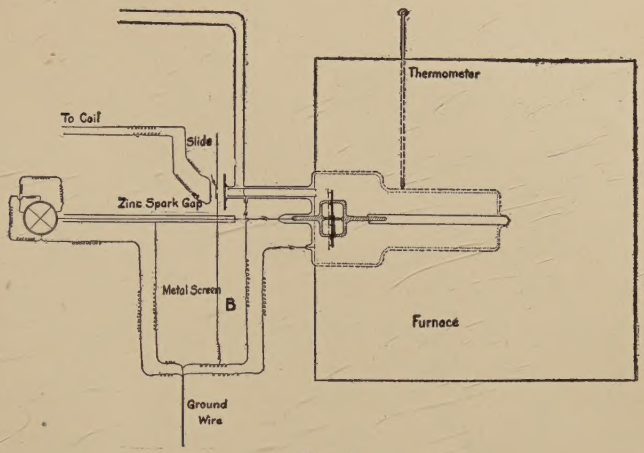

Fig. 1.

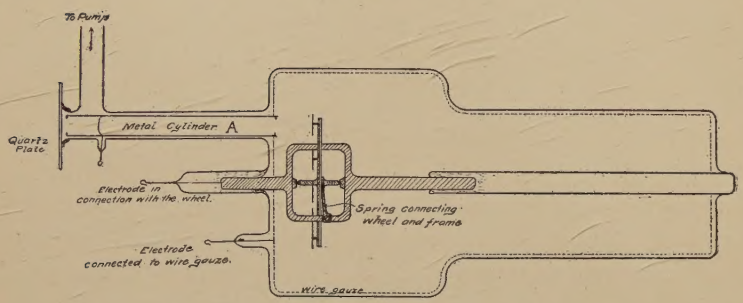

Fig. 2.

of any oils which might influence the photo-electric effect. They were finally heated, washed in alcohol, heated again, and mounted within the glass bulb without having their surfaces touched. Around the inner surface of the bulb and enclosing the wheel was placed a brass wire gauze which could be connected to earth or to the electrometer whichever was desired. In order that the different disks might occupy the same position with respect to the source of light and the wire gauze when they were exposed to the influence of the light, they were made to rotate in the same plane to within one one-thousandth of an inch or less. The ultra-violet light was admitted

to the bulb through a quartz plate sealed over the end of a projecting tube about 10 cm. long; within this glass tube was placed a co-axial brass cylinder, *A*, whose inside surface was coated with a dull black finish to avoid reflection and to prevent any photo-electric effects from its surface; its ends were closed with stops having openings of about 8 mm. diameter; it could be connected to earth or to the electrometer just as in the case of the wire gauze; the cylinder was placed close to the wheel so that the light would strike the disk which was being used and no part of the aluminium wheel would receive any light. Between the quartz plate and the source of light was a large metal screen, *B*, connected to earth, with an opening for the light; the opening was furnished with a shutter with which it was closed before an observation was taken and while the tests for inductive effects, etc., were being made.

The pump used to exhaust the bulb was a type of mercury pump with all connections of glass and capable of producing a good vacuum. The measurements on the photo-electric effect were made at pressures of .00001 mm. or less, as recorded by a McLeod gauge; the photo-electric effect was not influenced by pressures of this value as could be determined by working the pump until no gas could be pumped out and comparing values. Whenever a new bulb was sealed on, the temperature was always raised to about 400°C. at intervals; and this was continued until no more gas was given off; that this condition was realized was indicated by the fact that the gas from a bulb of 1,500 c.c. would collapse in a capillary tube of 1 mm. bore under a pressure of less than a centimeter of mercury; at the same time the reading of the gauge would show pressures ranging from .00001 mm. to zero pressure. This is merely intended to show that the pressure was below that which would influence the photo-electric effect. The pump was always kept running throughout a series of observations to be sure that no gas collected in the bulb.

The electric furnace which was used to regulate the temperature was a box made of sheet-metal with heavy asbestos linings. Porcelain spools were covered with asbestos, wound with iron wire, and supported on the four sides and the bottom of the box. When the furnace was joined to a 220-v.circuit a temperature of 500°C. could

quickly be obtained. The amount of current was regulated by rheostats in series with the furnace.

A spark between zinc electrodes was used as a source of ultra-violet light. At first considerable difficulty was experienced in obtaining results which would check within ten or twenty per cent. under apparently the same conditions. It was thought that the variations in the deflections of the electrometer needle could be accounted for by the unsteadiness of the hammer of the induction coil. Several devices, including a mercury-turbine interrupter, were substituted for the hammer but without success. Finally it was noted that the irregularities could be accounted for in the leak of the electrometer itself. When this was corrected the readings could be duplicated to within one or two per cent. A variable capacity was used in connection with the coil so that the character of the spark might be somewhat altered when necessary.

As a source of constant potential a battery of 900 elements was used; this was made of copper-zinc strips in water with one or two drops of H_2SO_4 added to every liter of water. This source of potential would remain constant for months at a time — or so long as the battery was kept dry and well insulated. This battery was used to charge the needle of the electrometer and the metal disks.

One of the most serious difficulties encountered in carrying out this experiment was due to the humidity of the atmosphere during the summer months, when the work was done. This was so great that the use of any of the best insulators was of no avail in retaining the small charges generated. Sulphur would insulate extremely well, but its use had to be dispensed with because it could not be made to form a plug that would not leak air when a high vacuum was obtained. The small amounts of electricity generated would leak over a length of 20 cm. of small quartz rod, even when heated and a small stream of dry air kept blowing over the rod. As a last resort it was decided to enclose the entire apparatus in a room made of building paper and attempt to dry the enclosure. The room was built and trays of H_2SO_4 and $CaCl_2$ were distributed throughout. Also a stream of dry air was kept continually flowing into the room. Tubes were inserted in the walls for the observer to breathe through. That this method of stopping the leak was capable of giving quite satisfactory results will be seen farther on.

III. OBSERVATIONS OF THE RELATION BETWEEN THE RATE OF DISCHARGE AND THE TEMPERATURE OF THE METAL.

In making these observations the wheel was joined to one pair of quadrants of the electrometer, while the other pair was joined to earth. The quadrants and the wheel were connected to the negative pole of a battery of 20 cells (20 volts), the positive pole being earthed, and a certain deflection was produced; the connection was then broken, the induction coil started, and finally the shutter was raised and the light was left on for 10 seconds; the needle came to rest again in perhaps 60 or 90 seconds, and the difference between the two deflections was taken as the leak due to the photo-electric effect. The leak of the electrometer was so small as to be inappreciable in comparison with that due to the light, so long as the temperature remained below 100° C. At temperatures above 100° C. a correction had to be made to eliminate the natural leak, which at 170° C. had become so large as to mask entirely the effect of the light. The cause of this leak is unknown. Positive and negative charges would disappear with equal readiness.

When an observation was made a certain temperature was established by means of the furnace and held steady by altering the current; then the wheel was rotated and the different metals were exposed in turn to the influence of the ultra-violet before the quartz window. Sometimes two or more series of readings would be taken before the temperature was changed in order to see if the values could be duplicated. The observations could be checked over a time of two weeks as closely as they could at any one time. The following table shows a representative series of observations. Here the metals are arranged in the order of their ability to discharge negative electricity; about eight times out of ten the order was as given in the table; at other times the nickel and the brass changed places, as may be seen by looking at the table. Their values are so nearly alike that conditions could not be sufficiently controlled to discriminate between them. It would perhaps seem that if any of the metals were to change places in the table, due to their nearly equal values, it would be the brass and the copper, instead of the brass and the nickel. The order of the other metals was always the same. Also, the results were just the same, whether

the wheel was joined to the electrometer, and the gauze and metal cylinder earthed, or the wheel earthed and the gauze and cylinder joined to the electrometer.

TABLE I.

Metal.	Rate of Leak in Scale Divisions.							
	T=25°	T=35°	T=40°	T=50°	T=65°	T=80°	T=100°	T=125°
Cu	25.10	25.15	25.20	25.25	25.00	25.05	24.80	24.75
Au	24.70	24.60	24.55	24.70	24.80	24.75	24.40	24.00
Ni	24.00	23.96	23.98	23.90	24.05	23.90	23.55	23.40
Brass	23.80	23.85	23.95	24.00	23.85	23.90	23.40	23.40
Ag	17.16	17.20	17.15	17.20	17.10	17.00	16.90	16.77
Fe	16.40	16.25	16.30	16.20	16.36	16.55	16.15	16.00
Al	14.90	15.00	14.85	14.86	15.06	14.90	14.40	14.55
Mg	11.00	11.12	11.10	11.05	11.00	10.97	10.90	10.90
Sb	4.00	4.00	4.10	4.00	4.00	4.00	3.90	3.95
Zn	1.20	1.30	1.31	1.35	1.20	1.20	1.24	1.10
Pb	.90	.90	.90	.88	.90	.90	.90	.90

The table shows that up to 100° C. if there is an increase in the rate of discharge of electricity from these metals due to the increased temperature, it lies within the errors of the experiment. The readings at 100° C. and 125° C. were corrected for the temperature leak as explained below and are therefore weighted with a larger error than are the readings at the other temperatures.

In some experiments made in May, 1905, by Professor R. A. Millikan and the writer concerning the effect of ultra-violet light with change of temperature upon an aluminium surface, the temperature could be raised to at least 350° before any very decided effect due to the temperature was noticed, yet some other disturbing element was present which hindered very consistent results being obtained. At 400° the metal would not hold a charge at all. Below in Table II. is given a series taken Tuesday, May 30, 1905. It will be seen from the table that the results check over the entire range of temperature with about the same degree of accuracy that several readings do at any one temperature. It was concluded from observations like these that if there was any influence of the temperature on the photo-electric effect it must be rather small. The method employed in taking these observations was to observe the leak of the electrometer for 30 seconds, then

throw the light on for 15 seconds and take the deflection at the end of 45 seconds and finally to observe the leak during another 30-second period. The sum of the two electrometer leaks during the 30-second periods was then subtracted from the change in the electrometer readings during the intervening 60-second period and this remainder taken as the leak due to the light.

TABLE II.

Temp.	Deflection in Scale Divisions.	Temp.	Deflection in Scale Divisions.	Temp.	Deflection in Scale Divisions.	Temp.	Deflection in Scale Division.
49°C.	18.0	272°C.	14.3	304°C.	15.5	78°C.	20.3
50	16.3	275	14.2	310	15.8	75	19.3
50	17.4	280	14.0	343	15.4	73	20.6
100	16.0	286	13.8	343	17.0	69	20.9
142	14.2	290	15.1	256	16.9	67	20.8
169	17.0	292	15.4	200	18.0	64	21.6
191	16.5	295	15.2	170	17.1	61	20.4
205	16.6	296	16.2	143	17.3	58	20.5
215	16.3	297	15.7	130	18.1	54	20.9
220	17.2	298	15.9	120	17.4	54	20.1
233	12.9	300	15.7	112	19.2	53	20.4
246	14.2	301	16.3	105	17.5	52	20.8
254	13.6	300	15.8	100	17.6	52	19.6
260	14.0	301	16.6	95	19.2	53	17.3
264	13.9	301	15.3	89	18.7	53	18.8
269	13.3	303	15.7	85	21.2	53	17.0

The variations in the readings shown in this table are doubtless wholly due to variations in the electrometer leak; at least when this source of error was eliminated in the manner described the values checked as shown in Table I. It would thus appear that there is no temperature effect on aluminium when the temperature is raised as high as 340° C. The bulb containing this disk went through a long series of heatings as high as 500° C. while the pump was kept running; an induction coil was run intermittently on the tube at the same time; this was carried on for at least ten days or two weeks before any observations were made. This possibly accounts for the fact that so high a temperature was reached before any discharge due to the heat was present; the large bulb with which the present observations were made could not be con-

veniently sparked with a coil; neither could it be heated as high as 400° C. except for periods of short duration.

On a separate bulb containing a small aluminium disk very consistent results were able to be secured to as high a temperature as 195° C. showing no increased discharge due to the temperature of the metal. This tube could be heated much hotter and the temperature was held at about 500° C. until no more gas appeared at the pump; in general, it was noticed that the more the tube was heated while the pump was kept running and the more the coil was used on the tube, the more consistent were the results and the higher the temperature that could be reached before the heat discharge influenced the results.

The relative values of the discharging powers of the different metals follows none of the ordinary series of metals; in general, it somewhat closely coincides with the melting point series, and yet it is hardly probable that the two phenomena have any necessary connection.

The following table showing the melting points of the metals and their order in the photo-electric series as determined in this investigation is inserted for comparison. The melting points are taken from J. Castell-Evans' physico-chemical tables and are those given by the author as the most probable values.

TABLE III.

Metal.	Melting Point.	Discharge Rate.
Cu	1050° C.	25.10
Au	1050	24.70
Ni	1450	24.00
Brass	——	23.80
Ag	968	17.16
Fe	——	16.40
Al	625	14.90
Mg	750	11.00
Sb	632	4.00
Zn	433	1.20
Pb	326	.90

Elster and Geitel arrange the metals of lower melting points in a similar series with reference to their power of discharging negative electricity in which just the opposite is shown, namely, the

lower the melting point the higher the value for the discharging effect. The following is their series to which has been attached the melting points.

TABLE IV.

Metal.	Melting Point.	Metal.	Melting Point.
Ru	38.5° C.	Li	180° C.
K	62	Mg	750
K + Na	—	Th	294
Na	97	Zn	433

IV. INFLUENCE OF TEMPERATURE UPON THE POSITIVE POTENTIALS ASSUMED BY THE DIFFERENT METALS.

In obtaining the positive potentials assumed by the different metals when exposed to ultra-violet light, the wire gauze and the metal cylinder were connected to earth; the wheel and its attached pair of quadrants were kept at zero potential, and the shutter in the screen, before the quartz window, was kept closed until an observation was ready to be made. Then the earth was removed from the electrometer and later the shutter was raised and the light kept on until the needle assumed a steady position. The time required for the needle to come to a permanent deflection varied with the different metals. If the source of light was placed farther away the time was longer but the final position of the needle was the same. Also, if the capacity was changed so as to alter the nature of the spark there was only a variation in the time necessary for the metal to assume this same potential. The average time necessary for the metals to assume the potentials given below was about 90 seconds; while at the same time one was unable to detect any leak in the electrometer over a period of five or six minutes. The values of the deflections could be repeated again and again to within less than one per cent. with those metals which assumed the higher potentials, the error being greater for the metals of lower potentials. That these readings were able to be duplicated to within so much smaller per cent. of error than in the previous set of observations on the rate of leak (Table I.) is probably due to the fact that in the observations on rate of leak the light was acting upon the metal for a comparatively short time, and might be less effective during one

ten-second interval than during another equal interval; while in this potential series, if the light was less effective during the first part of the period it would assume its normal value before the close of its period.

For the lower values of the temperature the readings could be made very accurately, but as soon as the discharge of electricity due to the heated condition of the metal was at all apparent, the potentials were reduced. The values of the potentials were checked up to about 100°C. and no increase was noticeable. The agreement between the different values of the potential (shown in Table V.) at different temperatures was of a somewhat higher order of accuracy than that shown in Table I. on the values of the discharge effect.

TABLE V.

Metal.	Deflection.					
	26°	40°	55°	60°	80°	95°
Ag	47.6	47.6	47.7	47.5	47.5	47.3
Fe	43.5	43.4	43.4	43.7	43.2	43.2
Au	43.1	43.2	43.1	43.0	43.1	43.0
Brass.	41.7	41.6	41.8	41.7	41.8	41.9
Cu	40.3	41.2	41.1	41.0	41.0	40.9
Ni	40.0	40.0	40.1	40.1	39.8	40.1
Mg	29.8	29.9	29.9	30.0	29.7	29.9
Al	26.2	26.2	26.2	26.1	26.3	26.2
Sb	14.0	14.1	14.0	14.1	14.1	14.0
Zn	7.0	7.0	7.1	6.9	6.8	6.7
Pb	00.0	00.0	00.0	0.00	00.0	00.0

Zeleny,[1] in his investigation on the effect of temperature upon platinum and iron exposed to ultra-violet light and surrounded by air at atmospheric pressure, observed a peculiar hysteresis effect, the discharges being greater when the metals were cooling than when they were rising in temperature. That particular effect was not noticed in these observations but a somewhat similar effect was observed; namely, that observations could be made at 50° to 60° higher when the temperature was rising than when it was falling. That is, if in the potential series 95° C. was the highest temperature at which good results could be obtained when the temperature was

[1] Zeleny, PHYSICAL REVIEW, Vol. 12, p. 321, 1901.

rising and if then the temperature was increased to say, 200° C., and the apparatus left to cool, then the first value that the heat discharge did not mask would be at about 40° or 30° C.

I desire to take this opportunity of acknowledging my obligations to Professors Michelson and Millikan for continued suggestions and assistance throughout this investigation, a considerable portion of which has been conducted in collaboration with the latter.

RYERSON PHYSICAL LABORATORY,
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September 1, 1906.